Particle-Wall Shear Stress Measurements within the Standpipe of a Circulating Fluidized Bed

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Abstract

Standpipes are used for the transfer of solids in circulating fluidized bed (CFB) systems. Though standpipes are essential to the operation of these industrially important systems, their hydrodynamics are poorly understood. In this research we have applied the one-dimensional mixture momentum balance to the standpipe. Neglecting the effects of acceleration, we have determined that the important forces are the gas phase pressure drop, weight of the bed, solid phase pressure drop, and the wall shear stress. The wall shear stress has been measured utilizing a new instrument developed jointly by WVU and NETL in Morgantown, called the shear vane. Since all other portions of the momentum balance are directly measured, the solids phase pressure drop was inferred as being the residual portion of the momentum balance. Correlations of these forces are included in this paper for a regime that is either packed or transitionally packed. An attempt to model shear stress and solids pressure has also been made assuming the wall shear stress is directly proportional to the solids pressure by a coefficient, α. Such a relationship is commonly used in bulk solid mechanics**.** From theory, it should allow us to predict the wall shear stress and solids pressured drop strictly from knowledge of the solids density and pressure drop along the standpipe height. Using this relationship, the estimated values of shear stress are up to 3 times the values measured. Further, the values of solids pressure estimated independently of shear stress measurements are up to half those predicted using measured values of shear stress. We anticipate the deviation between the

values will diminish once we have refined our measurements of the shear stress and have concurrently determined the coefficient, α, using a more accurate independent laboratory technique.

Introduction

The use of a standpipe for inerting and recirculation of solids to a fluidized bed riser reactor provides an attractive alternative for control of solids circulation within a circulating fluid bed process. An understanding of hydrodynamics of gas and solids flow in the standpipe is needed to assure optimization of solids circulation with minimum dilution of product gas.

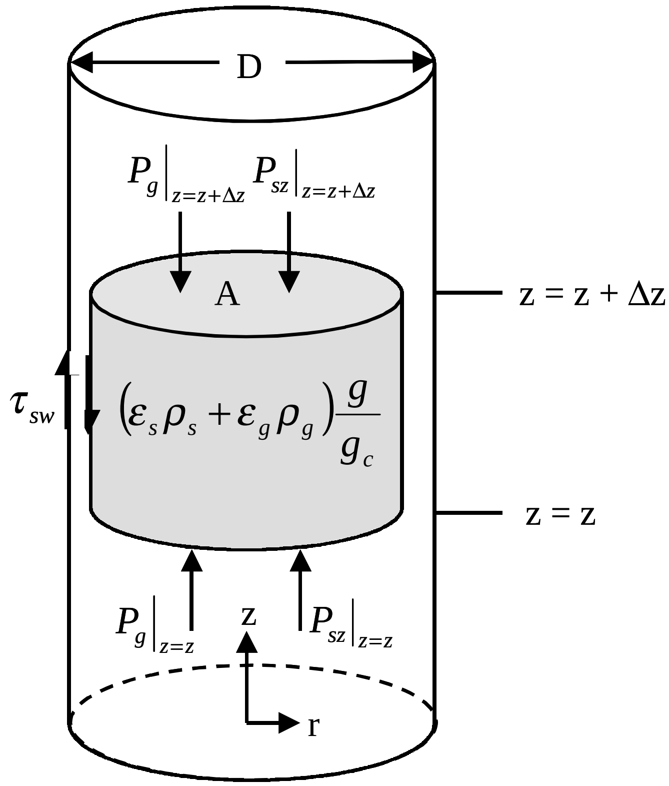
A circulating fluidized bed facility at the National Energy Technology Laboratory (NETL) is used to obtain the standpipe operational data for this study. NETL's unit is an atmospheric, cold flow, circulating fluid bed with a 12-inch (0.3048 m) diameter riser of 50-foot (15.24 m) height. The nominal solids circulation rate is 40,000 lb/hr (18,144 kg/hr). The 10-inch diameter standpipe is instrumented with aeration flow loops, differential pressure transmitters, load cells and a solids circulation (flow meter) velocity vane.

An appropriate model of forces in a standpipe is developed to close the force balance for the gas pressure, solids phase pressure, wall shear force, and solids body forces measured during operations of the circulating fluidized bed. The force balance model is applied over a wide range of continuously controlled solids circulation rates, riser inventories and standpipe aeration conditions.

Theory

To adequately model the hydrodynamics for standpipes we must first understand the important forces that contribute to the momentum balance. In our study we have investigated the wall shear stress and solids pressure gradient. These are two important forces that have little experimental information available in the literature. Consider the section of standpipe in the Figure 1 below.

Figure 1: Standpipe Force Balance



The momentum balance on the total mixture is as follows:

$$\frac{\partial}{\partial t}\iiint_{cv}\varepsilon_s\rho_s v_{s,z}dV + \frac{\partial}{\partial t}\iiint_{cv}\varepsilon_g\rho_g v_{gz}dV + \iint_{cs}\varepsilon_s\rho_s v_{sz}\vec{v}_s\cdot\vec{n}dA + \iint_{cs}\varepsilon_g\rho_g v_{gz}\vec{v}_g\cdot\vec{n}dA = \sum F_z \qquad (1)$$

The first two terms are the accumulation of momentum for the gas and solids phase, and because the system is assumed to be in steady state, they are assumed to be zero. The remaining two terms stand for the net outflow of momentum. If we assume plug flow and that bulk density is constant across the cross section, the net outflow of momentum can be expressed by equation (2).

$$\iint_{cs}\varepsilon_s\rho_s v_{sz}\vec{v}_s\cdot\vec{n}dA + \iint_{cs}\varepsilon_g\rho_g v_{gz}\vec{v}_g\cdot\vec{n}dA = \dot{m}_g\left(v_{gz}\big|_{z=z} - v_{gz}\big|_{z=z+\Delta z}\right) + \dot{m}_s\left(v_{sz}\big|_{z=z} - v_{sz}\big|_{z=z+\Delta z}\right) \quad (2)$$

If there is steady state flow and the solids volume fraction is constant, then the velocity in equals the velocity out and the right hand side of equation (2) is zero.

The right hand side of equation (1) is the, sum of the forces, can be expanded as follows:

$$0 = \frac{\pi D^2}{4}\left(P_g + P_{sz}\right)\Big|_{z=z} - \frac{\pi D^2}{4}\left(P_g + P_{sz}\right)\Big|_{z=z+\Delta z} + \tau_{gw}(\pi D\Delta z) + \tau_{sw}(\pi D\Delta z) - \left(\varepsilon_s \rho_s + \varepsilon_g \rho_g\right)\frac{g}{g_c}\left(\frac{\pi D^2}{4}\Delta z\right) \quad (3)$$

This equation shows that the forces acting on the control volume are gas phase pressure, solids phase pressure, gas-wall shear stress, solids-wall shear stress, gas phase weight, and solids phase weight.

Dividing by Δz, and taking the limit as Δz goes to zero results in:

$$-\frac{\partial P_{sz}}{\partial z} - \frac{\partial P_g}{\partial z} + \frac{4\tau_{sw}}{D} + \frac{4\tau_{gw}}{D} - \rho_g \varepsilon_g \frac{g}{g_c} - \rho_s \varepsilon_s \frac{g}{g_c} = 0 \quad (4)$$

The wall shear stress and body force terms are considered small for the gas phase and are ignored (Jones 1985, Picciotti, 1995), leaving equation (4) in terms of process variables.

$$-\frac{\partial P_{sz}}{\partial z} - \frac{\partial P_g}{\partial z} + \frac{4\tau_{sw}}{D} - \rho_s \varepsilon_s \frac{g}{g_c} = 0 \quad (5)$$

The gas pressure drop is experimentally determined using differential pressure transducers and the weight of the bed is determined by assuming solids volume fraction deviates little from the packed state. Shear stress measurements are obtained with the shear vane discussed in the experimental section. The solids pressure was the only term not measured directly. However, it can be inferred by difference from the other measurements. Rearranging equation (3) and neglecting gas phase wall shear stress and gas phase body force results in equation (6).

$$\frac{\Delta P_{sz}}{\Delta z} = -\rho_s \varepsilon_s \frac{g}{g_c} + \frac{4\tau_{sw}}{D} - \frac{\Delta P_g}{\Delta z} \quad (6)$$

Solids wall shear stress and solids phase pressure can be estimated independently of our shear stress measurements. Existing theory states that the wall shear stress and axial solids pressure should be related according to equations (7) through (9). Note that 1/K is the Janssen coefficient (Jones 1985, Davidson 1990, Picciotti, 1995).

$$\tau_{sw} = \alpha P_{s,z} \quad (7)$$

$$\alpha = \frac{\tan \delta_w}{K} \quad (8)$$

$$\frac{1}{K}=\frac{1-\sin\delta}{1+\sin\delta} \tag{9}$$

The constant, α, is a property of the bed material. Picciotti, 1995 describes it as representing the material's resistance to flow. He further states that it balances the internal property of the solids to sustain motion with the external resistance to stop motion. A higher value of α gives a higher resistance. The constants δ and δ_w are the internal angle of friction and angle of wall friction respectively.

We have determined α by measuring δ and δ_w using an approximate visual experiment (Zenz, 1960). By substituting equation (7) into equation (5), the following expression is obtained after mathematical manipulation (Picciotti, 1995).

$$P_{sz}\Big|_{z=z1}=\frac{D}{4\alpha}\left(e^{\frac{-4\alpha}{D}(z_2-z_1)}\right)\left(\frac{\Delta P_g}{\Delta z}+\frac{4\alpha}{D}P_{sz}\Big|_{z=z2}-\rho_s(1-\varepsilon_c)\frac{g}{g_c}\right)-\frac{D}{4\alpha}\left(\frac{\Delta P_g}{\Delta z}-\rho_s(1-\varepsilon_c)\frac{g}{g_c}\right) \tag{10}$$

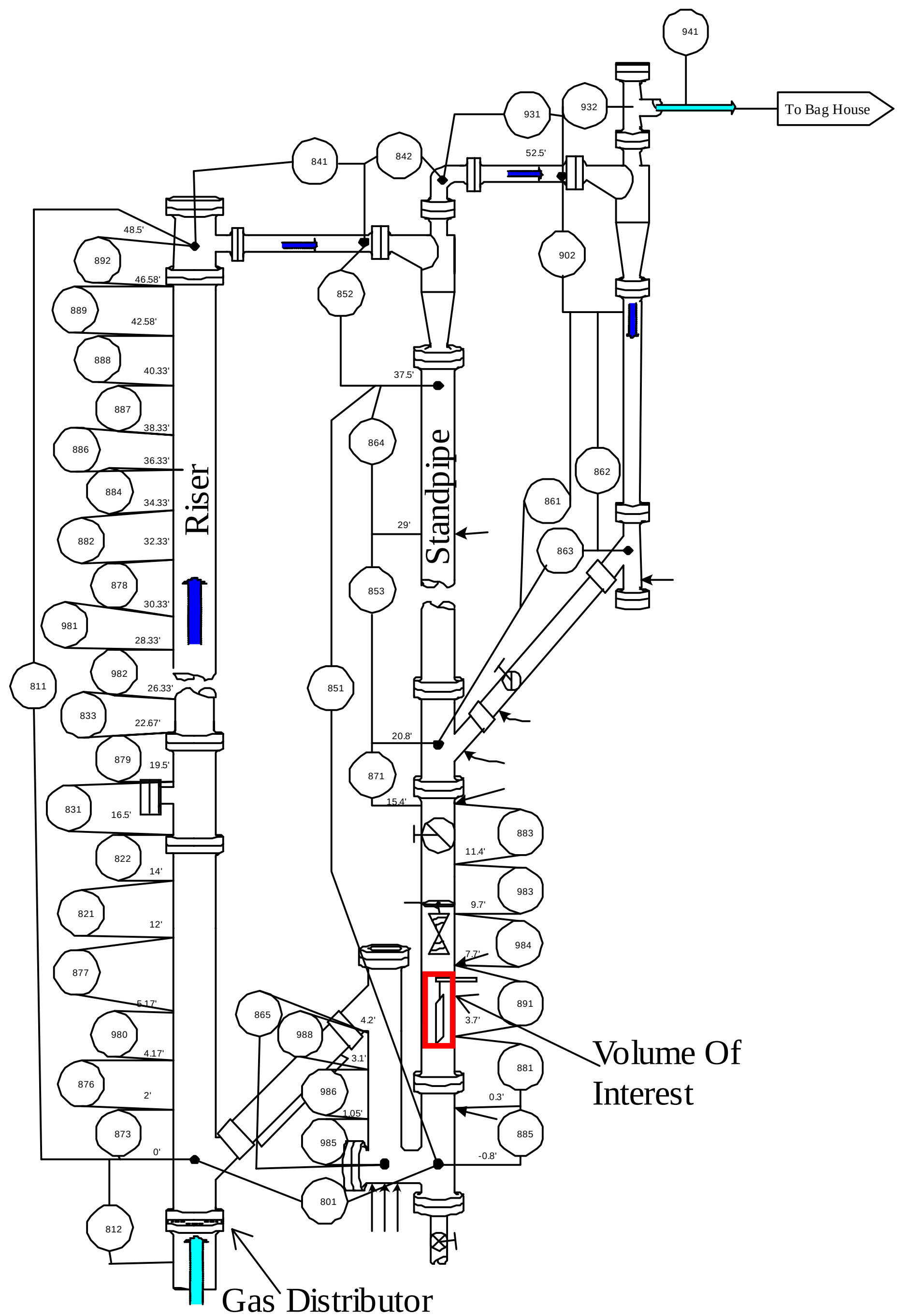
Assumptions made in the derivation of this equation are constant solids volume fraction, constant gas pressure drop per unit length, and that the bed is in an active state of stress. Because of the assumption of constant gas pressure drop per unit length, this equation is applied over several small sections of the standpipe where measured values of the gas pressure are known and the incremental values of the solids pressure along the standpipe can therefore be determined. The procedure used to determine the solids pressure is a step wise one, starting at the top of the bed. Assuming a zero solids pressure at the top of the bed, a solids pressure at some interval into the bed is calculated. Using this solids pressure at the bottom of the first interval as the top pressure for the next interval, solids pressures are calculated until the location of intent is reached. Also, equations (7) and (5) can be used together to estimate a solids wall shear stress.

Two different methods have been presented to estimate solids phase wall shear stress and solids phase pressure drop. The first is to experimentally measure gas phase pressure and solids phase shear stress of the control volume, and then to use these measurements to calculate the solids phase pressure drop assuming a constant solids volume fraction and using equation (6). The second method is to measure solids phase pressure drop at increments along the standpipe and measure the height of the bed. Then equation (10) is applied successively down the standpipe until the solids pressure across the control volume of interest is known. These solids pressure values can be used with equation (7) to find shear stress. Take note that the second method is independent of direct shear stress measurements, and that both methods assume a constant solids volume fraction.

Experimental Set-up

Circulating Fluidized Bed: All experimental work was carried out at the DOE's National Energy Technology Laboratory located in Morgantown, WV. The CFB is configured as shown in the Figure 2, and is one of the three largest cold flow public sector facilities in the U.S.A. that generates data for public distribution. The riser is 12-inch (30.48 cm) I.D. and 50 ft (15.24 m) in height with a standpipe I.D. of 10-inch (25.4 cm). Circulation rates of 120, 000 lb/hr (54,431 kg/hr) have been reached with a nominal rate of 40,000 lb/hr (18,144 kg/hr). The system is rated at 100 psi (690 kilo-pascals), but most of the tests for this study are carried out at near atmospheric pressure and ambient temperature. The standpipe and riser are equipped with differential pressure transducers at increments along the height. Mass flow controllers meter the aeration to the standpipe for control of the solids flowrate. Solids are transported from the standpipe to the riser through a fully fluidized nonmechanical valve. The effluent solids stream from the riser is separated from the carrier gases in primary and secondary cyclones and returned to the standpipe.

Figure 2: NETL Circulating Fluidized Bed

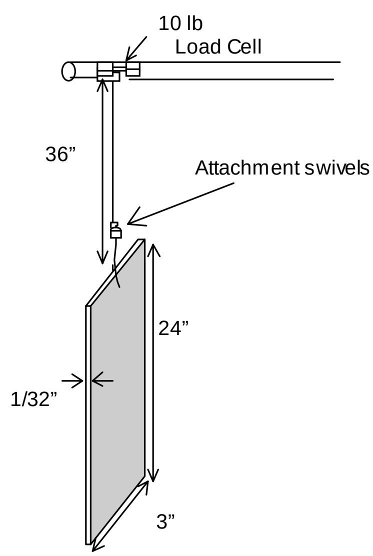


Bed Materials and Properties: The material utilized in this study is coke breeze. The material is a Geldart Group B (Gidaspow, 1994) with an average particle diameter of 250 micron. Its bulk density is 54-56 lb/ft^3 (865-897 kg/m^3) with a particle density of 110.8

lb/ft^3 (1,762 kg/m^3). Void fractions under vibrated and minimum fluidization conditions were measured as 0.50 and 0.56 respectively. The minimum fluidization velocity is 0.072 ft/s (0.022 m/s) with a sphericity of 0.84. Utilizing the technique of Zenz (1960), the internal angle of friction, δ, has been estimated to be 73-77°. The angle of wall friction, δ_w, of the shear vane, which is fabricated of galvanized sheet metal, was estimated as 30-35°. Using equations (8 and 9) the value of alpha ranges from 0.008 to 0.015. The value of alpha used in this work is 0.013.

Description of Shear Vane: The shear vane is a device used to measure shear stress within the standpipe, developed concurrently by WVU and NETL. It is a thin, flat metal sheet suspended from a 10 lb load cell probe. The load cell measures the weight of the vane plus the forces the bed particles exert on it as they move past it. The vane is inserted radially and hangs along the centerline of the standpipe. The top of the vane is located about 7.7 feet (2.35 m) from the bottom of the standpipe. See Figure 2 for the control volume of interest. The vane is 3 inch (7.62 cm) in width, 24 inch (60.96 cm) in length, and 1/32 inch (0.79 cm) in thickness. See Figure 3. The active area of the shear vane is 1/5th the surface area of the 10" pipe per unit length. It is assumed that the shear stress measured by the vane along the centerline of the pipe is the same as the shear stress at the wall. This is a reasonable assumption if we assume plug flow in the standpipe.

Figure 3: Shear Vane Schematic



Experimental Results

The mass flowrate of solids through the standpipe is a function of the amount of air used in partial fluidization. Figure 4 is a typical plot showing how the circulation rate varies with a monotonic increase in aeration. The flowrate of air was ramped from 55 to 405 scfh at a rate of 20 scfh/min. It has been shown at NETL that at this gradual ramp rate, measured variables obtained from the CFB reflect a near steady state relationship. That is, the time dependent effects can be neglected. The controlling dependence of circulation rate on standpipe aeration is quantified with a new solids flow measurement device, developed at NETL (Ludlow, 200).

Figure 4: Solids Circulation versus Aeration (monotonically increasing with time)

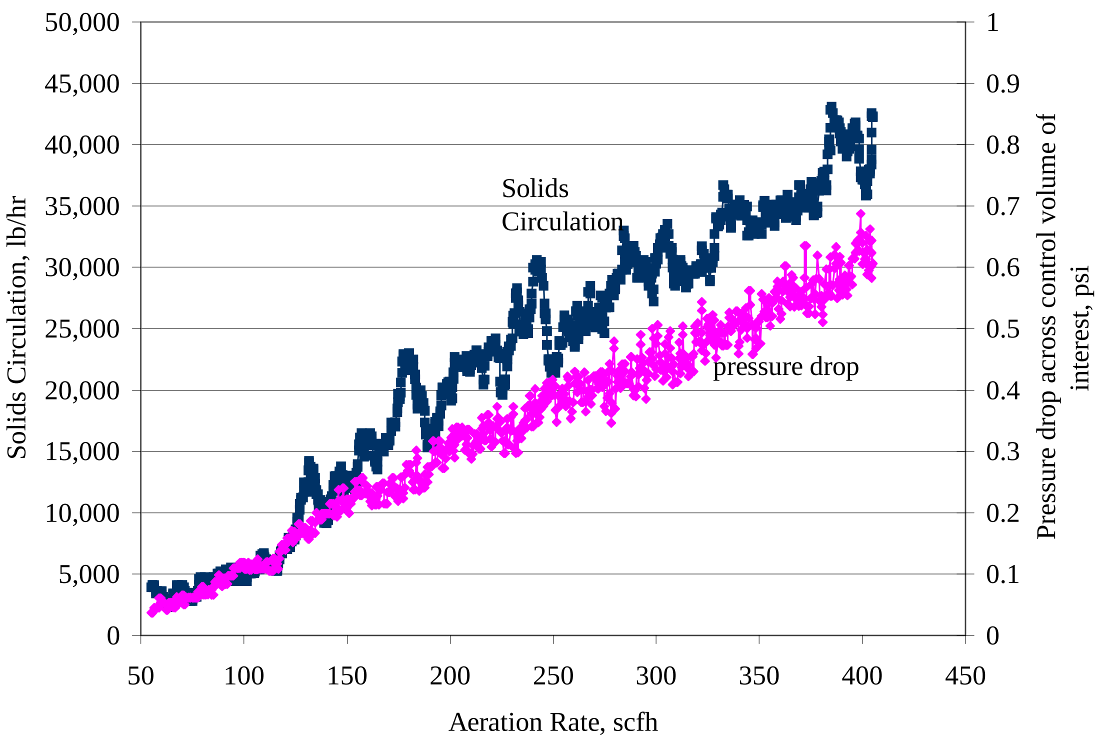


Figure 5 illustrates how the gas phase pressure drop, wall shear stress, and solids phase pressure drop vary as a function of solids circulation. The bulk density of the bed is assumed constant in this plot. All of the forces relate to the control volume of interest highlighted in Figure 2. To compare the relative magnitude of these forces the aeration rate was ramped from 55 to 405 scfh. This data is taken from the same ramp in Figure 4. During the ramp the gas phase pressure drop ranged from 2 to 21% percent of the total force, and the wall shear stress ranged from 27 to 6%. The solids phase pressure did not vary much from 25% of the total force. Because solids pressure is estimated by difference (equation (6)), the weight of the bed never changed appreciably from 50% of the total force. Take note that solids pressure was not measured, it was calculated from equation (6).

Figure 5: Momentum Balance Components versus Solids Circulation

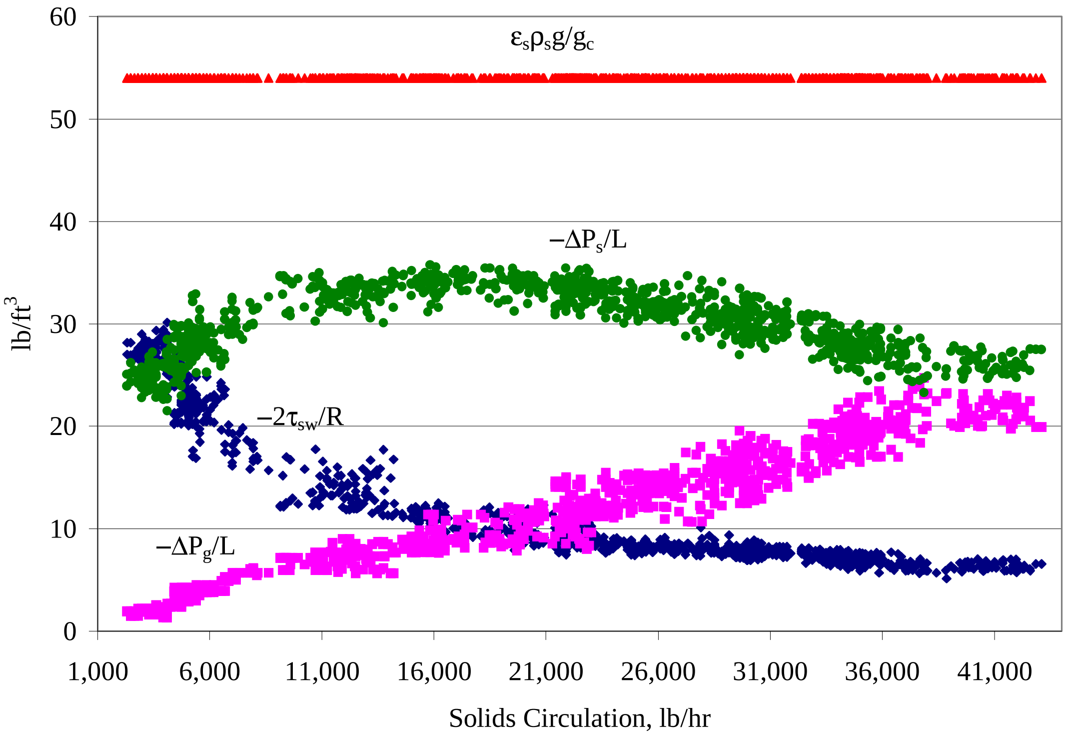
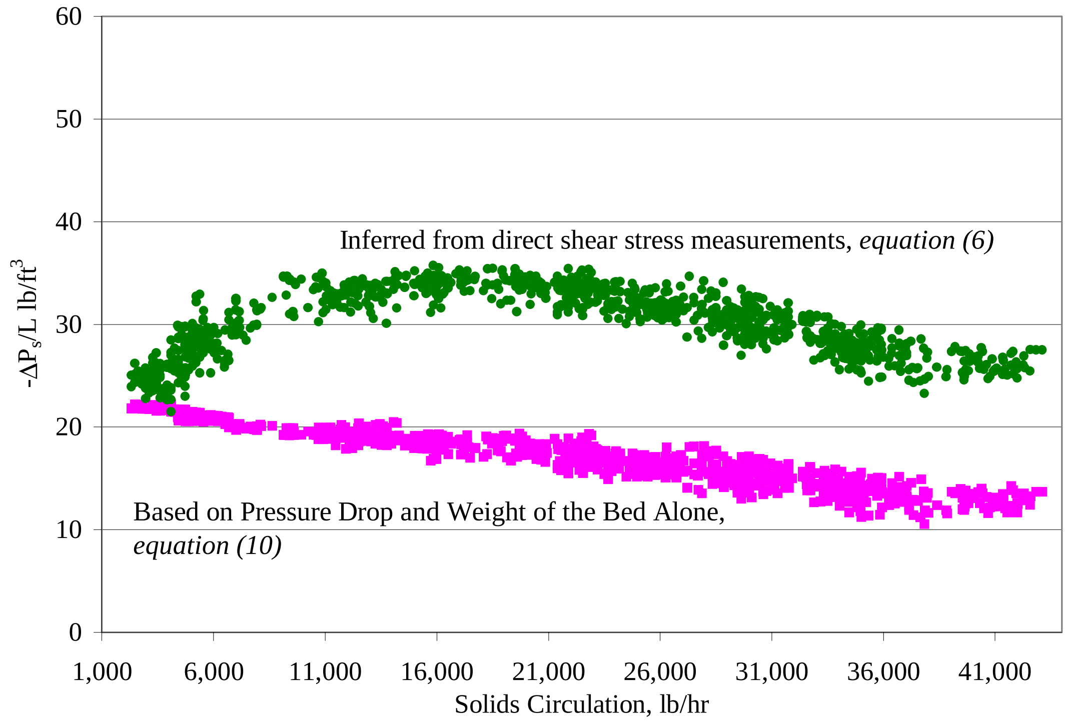


Figure 5 shows us that the shear stress and solids phase pressure drop are major components of the mixture momentum balance that must be quantified if we are to have a thorough understanding of standpipe hydrodynamics.

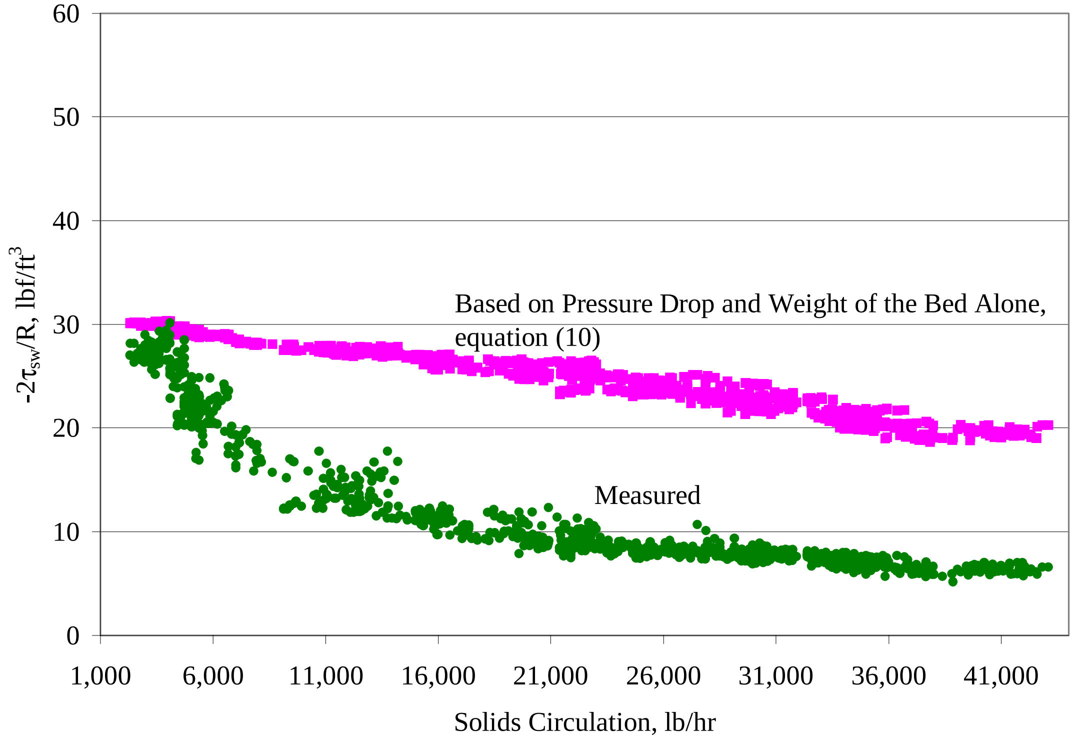
Figure 6 graphs the solids phase pressure drop as determined experimentally by difference and from equation (10) versus solids circulation. The two methods utilize experimentally determined gas pressure drop and assume a constant void fraction. Solids pressures calculated using equation (10) are lower in value then the solids pressure from shear stress measurements, but follow a similar trend at solids circulation rates larger then 10,000 lb/hr. The two methods come closer together for solids circulation rates less then 10,000 lb/hr. However, for lower circulation rates the method using equation (6) increases with increasing mass circulation, while the method using equation (11) decreases with increasing mass circulation rate.

Figure 6: Estimated Values of $-\Delta P_s/L$ versus Solids Circulation



In Figure 7 we have plotted predicted and measured values of the shear stress as a function of solids circulation rate. Again the predicted values were obtained using equations (6) and (10). Here the predicted values over estimated the measured values, and similar to the solids pressure, the results show very different trends at mass circulation rates below 10,000 lb/hr where the measured values drop more steeply with increasing mass circulation.

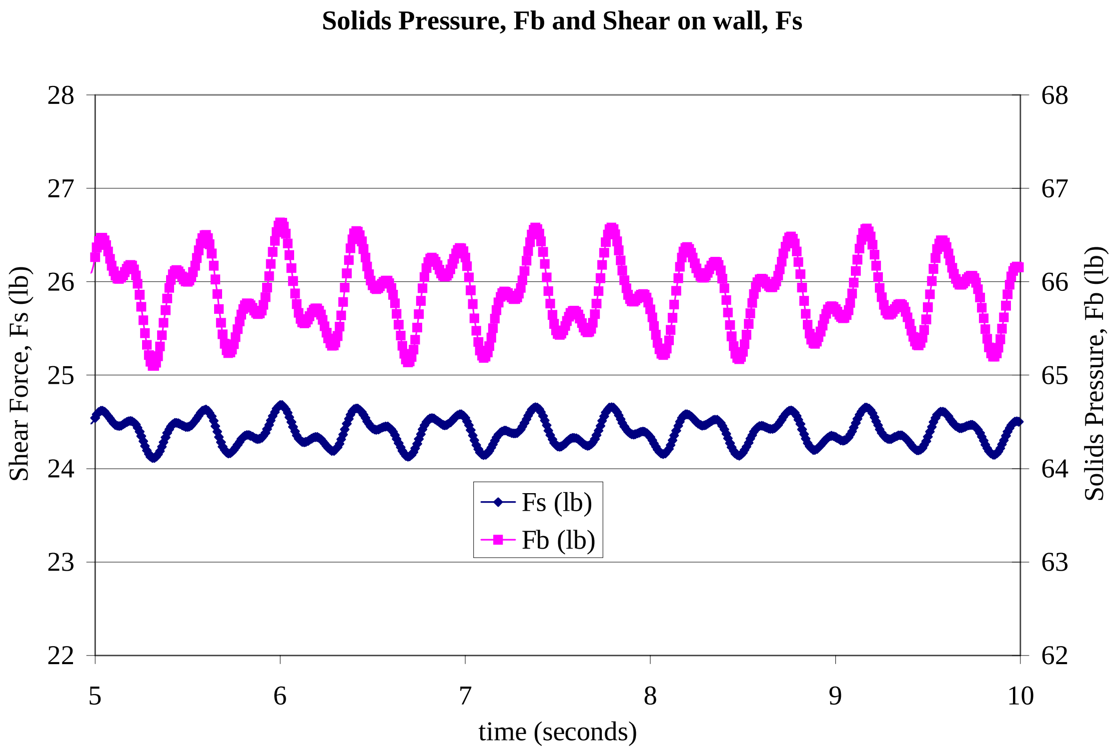
Figure 7: Measured and Estimated Values of $-4\tau_{sw}/D$ versus Solids Circulation



Dynamic Exhibited by Model

Having made the assumption of steady state condition with no solids acceleration presented above serves to allow solids pressure and shear force to be quantified. A dynamic model was then developed to retain the mass acceleration term. As a simplistic evaluation, the model was developed from a force and momentum balance for two segments of a standpipe.

Figure 8: Dynamic Moving Bed Forces



Results of the dynamic model of the solids pressure between coupled standpipe segments show sustained oscillations originating within the standpipe force balance in Figure 8 with otherwise steady state conditions of aeration and solid inventory. The resulting solids velocity of this simple model exhibits similar sustained dynamic observed in Figure 4 circulation rate. Further experimental measurements are underway to validate this form of shear stress dynamic chaos.

Conclusions

Solids wall shear stress has been experimentally measured. Based on these measurements, solids phase pressure has been estimated. From these estimates solid phase pressure and solids wall shear stress are important forces in the momentum balance that cannot be ignored. Shear stress ranges from 27 to 6% of the total force on a control volume of bed material in which the aeration was ramped from 55 to 405 scfh. Solids pressure was approximately 25% of the total force.

An attempt to estimate solids wall shear stress and solids pressure independently of shear stress measurements has been made. These estimates show similar trends to the measured shear stress for mass circulation rates above 8,000 lb/hr. However, the values of shear stress estimated are up to 3 times the values measured. Further, the values of solids pressure that are estimated independently of shear stress measurements are up to half those predicted using measured values of shear stress. We think these differences will diminish once we have refined our measurements of solids wall shear stress and the coefficient, α.

Nomenclature

A	Surface area of the control volume
D	Diameter of the standpipe
g	Acceleration due to gravity
g_c	Universal gravitational constant
F_z	Forces acting on the control volume in the z-direction
H	Height of standpipe
$1/K$	Janssen coefficient
L	Length of the control volume
$\dot{m}_g$	Mass flowrate of gas phase
$\dot{m}_s$	Mass flowrate of solids phase
$\vec{n}$	Outward drawn normal unit vector
P_g	Gas phase pressure
P_s	Solids phase pressure
P_{sz}	Solids phase pressure in the axial direction
V	Volume of control volume
$\vec{v}_g$	Gas phase velocity vector
v_{gz}	Gas phase velocity in the axial direction
$\vec{v}_s$	Solids phase velocity vector
v_{sz}	Solids phase velocity in the axial direction
α	Resistance of the material to flow
δ	Internal angle of friction
δ_w	External angle of friction
ε_g	Void fraction of gas phase
ε_s	Volume fraction of the solids phase
ρ_g	Density of gas phase
ρ_s	Density of solids phase
τ_{sw}	Solids wall shear stress

References

Jones, P.J. and L.S. Leung. (1985). "Downflow of Solids through Pipes and Valves," in J.E.Davidson. *Fluidization second Edition*. London: Academic Press.

Ludlow, J. Christopher, Lawrence J. Shadle, and Madhava Syamlal. (2002). "*Development of Spiral Device for Measuring Solids Flow*, " to be presented at the 7th International Conference on Circulating Fluidized Beds, 2002

Miller, A. and D. Gidaspow. (199). "Dense, Vertical Gas-Solids Flow in a Pipe," *AIChE Journal*. 1992, 38, 1801

Mountziaris, Triantafillos and Roy Jackson. (1990), "The Effects of Aeration on the Gravity Flow of Particles and Gas in Vertical Standpipes," *Chemical Engineering Science*, Vol. 46, No.2 pp. 381-407

Picciotti, Marcello. (1995), "Specify standpipes and feeder valves for packed beds," *Chem. Eng. Prog*. 91(1),54-63.

Zenz, Frederick A. and Donald F. Othmer. (1960). *Fluidization and Fluid-Particle Systems.*New York: Reinhold publishing Corporation.